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A STUDY OF ABLATOR PRODUCIBILITY AND REFURBISHMENT METHODS

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ABSTRACT

This paper describes a study of fabrication, installation, and removal methods for ablative thermal protection systems that was conducted using a lifting-body space vehicle airframe as a full-size demonstration test bed for prototype hardware.

INTRODUCTION

The Space Shuttle Orbiter must withstand surface temperatures during ascent and entry that can exceed 3000°F in some areas. Ablative heat shields are potential backup candidates for protecting the spacecraft's metal structure from this environment, but with the repeated use of the Shuttle vehicle, the unit cost of ablators must be reduced to make them competitive with other systems. These efforts have been concentrated on reducing fabrication costs and simplifying replacement. Previous studies have shown that although the lightest installation method is direct bonding, where the ablator is bonded directly to the orbiter structure, refurbishment time and costs for this approach are excessive. Accordingly, the goals of this study were to improve the producibility of the basic ablator, to develop more efficient refurbishment methods for the direct bonded system, and to determine the effects of these improvements on the cost of the Space Shuttle program.

APPROACH

The Martin Marietta SLA-561 ablator was selected as the baseline material for this study since it has been fully characterized on the Viking program and is a suitable material for Shuttle application. This system consists of an elastomeric silicone ablator supported in a glass-phenolic honeycomb core matrix and bonded to the vehicle structure.

The large size of the Shuttle vehicle precludes the use of conventional ablator application methods, such as those used on PRIME and Viking. In these programs, the core was bonded to the vehicle using high-temperature adhesive and the entire vehicle was placed in a vacuum bag and cured in an oven under vacuum pressures. After curing, the core was hand-filled with the uncured ablator mix and the vehicle was again placed in a vacuum bag and cured in an oven under vacuum pressures. Then the excess was hand-machined until the proper ablator thickness was obtained. In contrast, the only practical approach for Shuttle is to apply the ablator in segments (such as prefabricated and cured panels of the proper thickness) using room-temperature-curing adhesives that require very low pressures. This approach has been demonstrated to be satisfactory in terms of thermostructural reliability during development of the Viking heat shield, as well as on other IR&D programs. Using this approach as a baseline, we established a program to study and improve the producibility of the basic SLA-561 ablator, develop more efficient refurbishment methods, and determine the effects on the cost of the Space Shuttle program.

In an effort to conduct meaningful ablator fabrication and refurbishment demonstrations, the Martin Marietta SV-5J (X-24 configuration) lifting body vehicle (Fig. 1) was used as a representative flight vehicle structure. Three ablative panels with compound curvature (totalling 22.5 sq ft) were fabricated and installed on the vehicle, and fabrication costs were generated and projected to the Shuttle program.

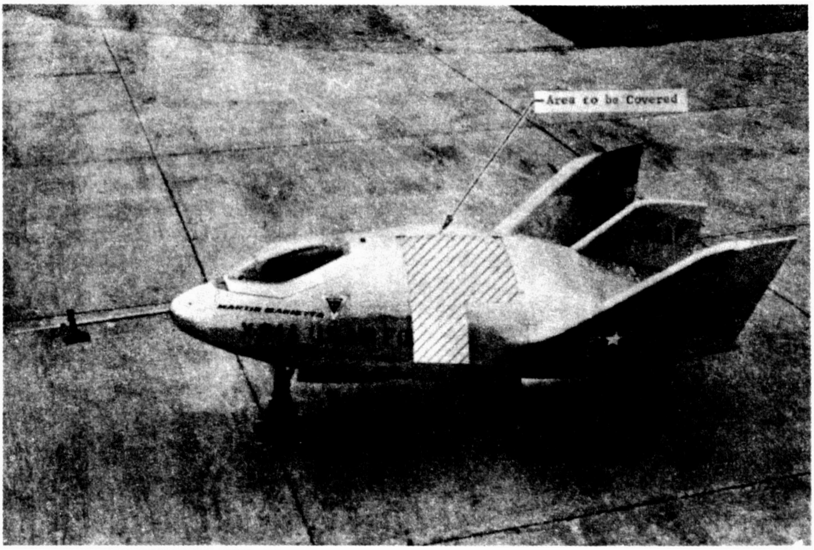

Fig. 1 SV-5J Area to Be Covered

FABRICATION

All previous methods for packing honeycomb core had relied on high localized pressure to force ablative material into the cells. Rivet guns and multiple autoclave pressure cycles were generally used in an effort to load the panels to the desired density. Combinations of hand packing and auxiliary pressure always resulted in severe lateral and in-depth density gradients because of the poor flow characteristics of the material. However, even with these methods the typical density gradients were approximately 3 lb/ft^3 (pcf) through the thickness of a 2-in. panel, and over 1 pcf across the surface. In addition, voids occurred throughout the material and were difficult to control.

To overcome this situation, we developed a method that reverses the procedure and vibrates the core into the prepacked ablator mix while controlling the density gradients to within ± 0.5 pcf. A vibration assembly, consisting of four compression springs mounted between a fixed plate and a floating plate, with an air-driven vibrator motor (16,000 rpm) attached to it, was mounted in a Dake bearing press and held with tension springs (Fig. 2). Panels up to 13 in. by 13 in. by 2½ in. thick were fabricated by placing uncured molds of ablator material into the press and pressing the vibrating core into it. Checks on the first few panels formed in this manner indicated that the density at the center of the thickness was greater than that at the top and bottom surfaces due to the material being compacted from both sides. Subsequent trials indicated that packing the panels from both sides prevented this gradient. This was accomplished by partially packing the mold frame, vibrating the core into it, inverting the packed core and frame, partially loading a second mold frame, and pressing the partially filled core into it. After loading the panel with ablator, the assembly was vacuum-bagged and cured in an oven under a vacuum pressure of 15 in. of Hg. Our experiments indicated that a 65%/35% ratio produced density gradients within ± 0.5 pcf.

The panels planned for installation demonstrations on the SV-5J vehicle were approximately 29 in. by 48 in. by 1¼ in., which required increasing the area of the prototype vibration press by approximately four times. A vibration assembly consisting of four subassemblies, each similar in size and construction to the one previously described, was made and mounted in a 36-in. by 48-in. platen press (Fig. 3 and 4). Panels large enough to be installed on the SV-5J were successfully vibration-packed using this assembly (see Fig. 5).

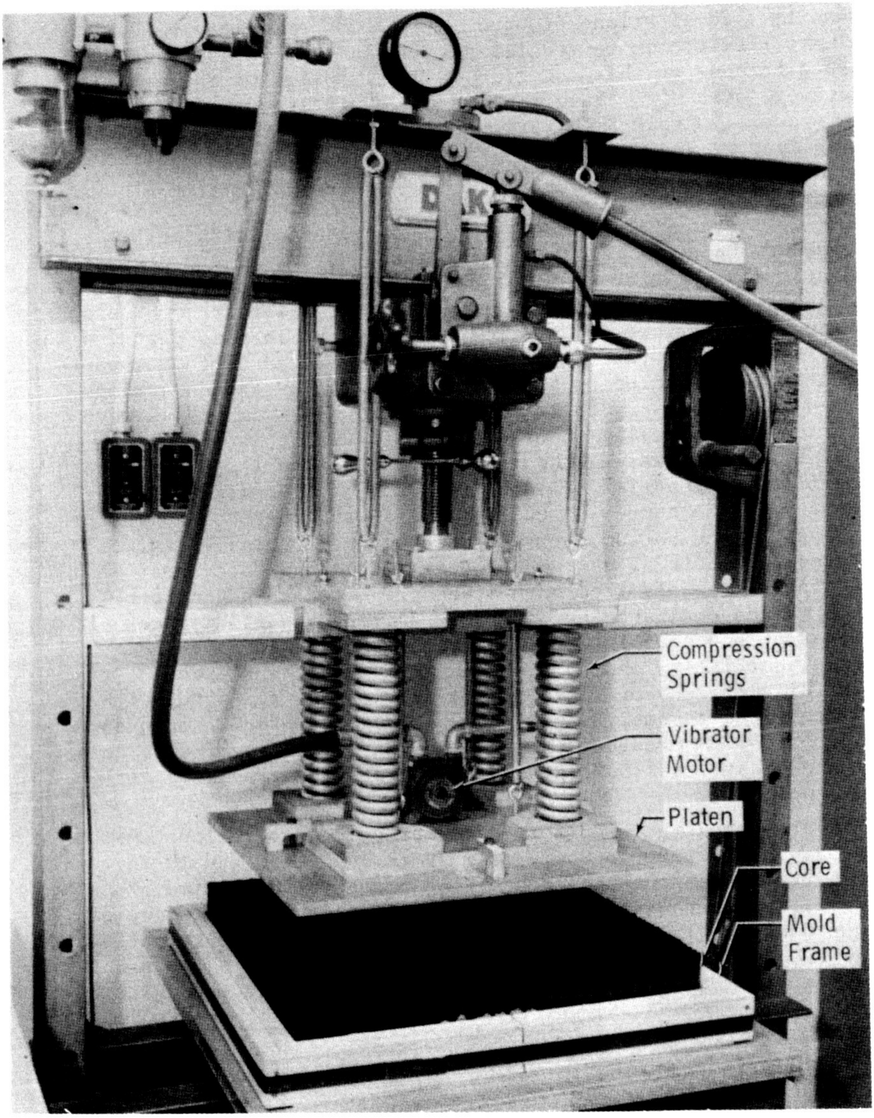

Fig. 2 Dake Vibrator Press

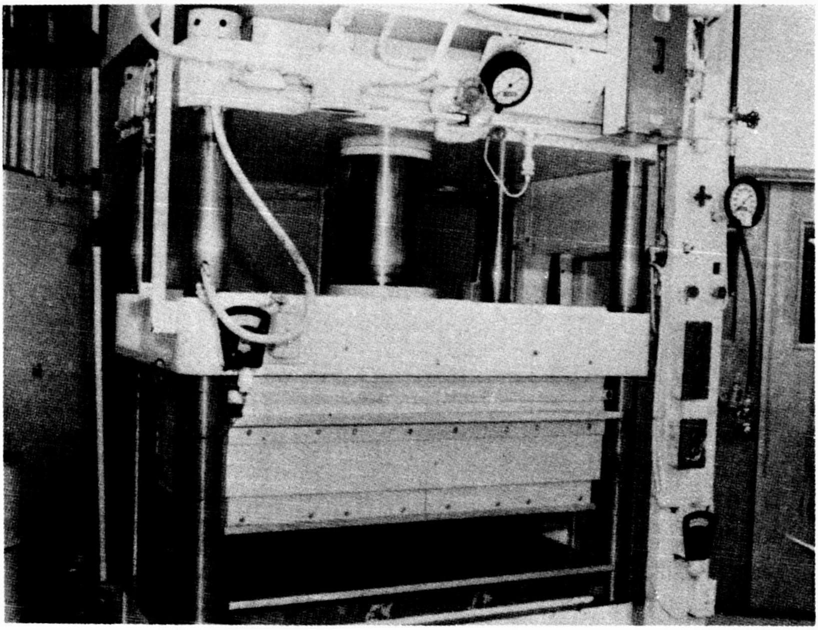

Fig. 3 Enlarged Press Assembly (36 in. x 48 in.)

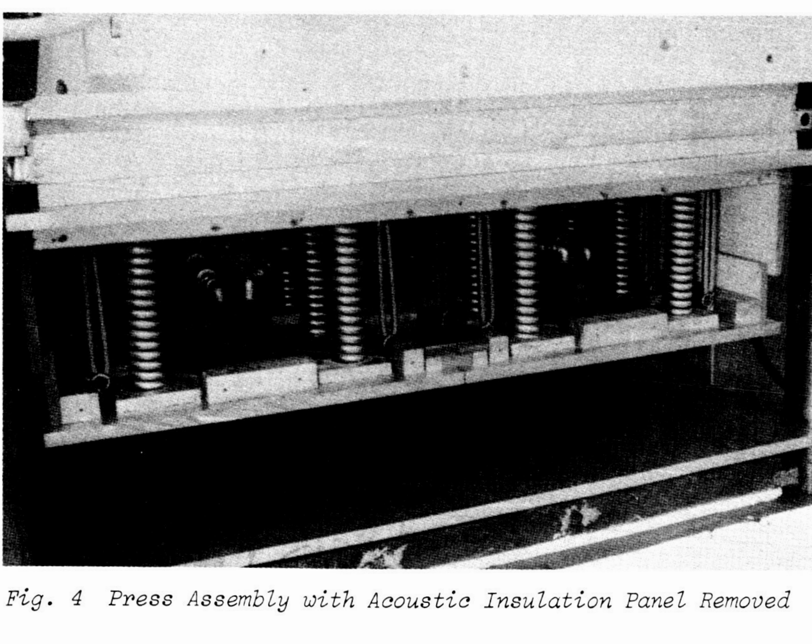

Fig. 4 Press Assembly with Acoustic Insulation Panel Removed

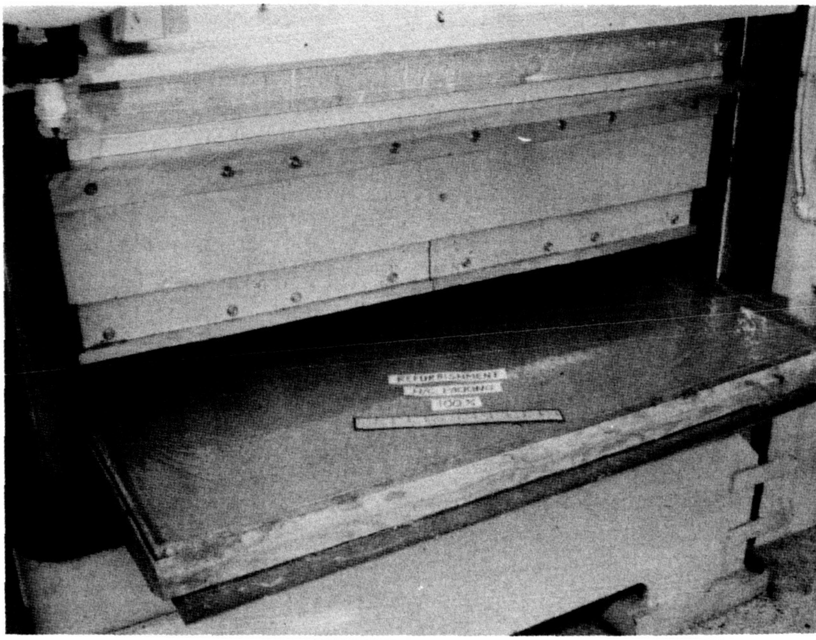

Fig. 5 Completed Panel after Filling the Remaining 35%

REFURBISHMENT

The reuse capability of the Shuttle requires that the ablator be removed and replaced after each flight at a reasonable cost. This aspect of the requirement is unique to the Shuttle since all ablator applications to date have been for single exposures. To match the surface contours of the SV-5J vehicle, splashes (laminated sheets of fiberglass, molded in place against the vehicle surface) were taken in selected areas. These splashes were then used to make the vacuum-forming and trim tools used in fabricating the ablator panels, as well as the pressure-bag restraining fixtures used to apply the ablator to the vehicle (see Fig. 6 and 7).

The ablative panels were fabricated by cutting the core to the proper thickness, vibration-packing the core into the ablator, placing the flat, uncured panel on the vacuum forming tool and forcing it to take the shape of the tool, and vacuum-bagging and curing the panel in an oven. After being cured the panel was hand-machined to remove the excess head material down to the presized core, and then trimmed to size. At this point, the panels were ready for installation on the vehicle. Figures 8 through 12 show the major steps in the panel fabrication sequence after the core has been vibration-packed.

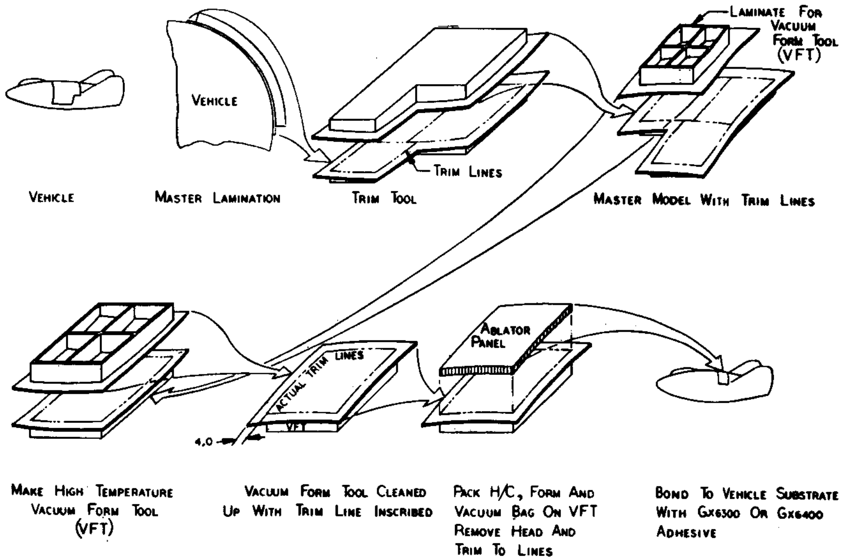

Fig. 6 Tooling Technology for Refurbishment

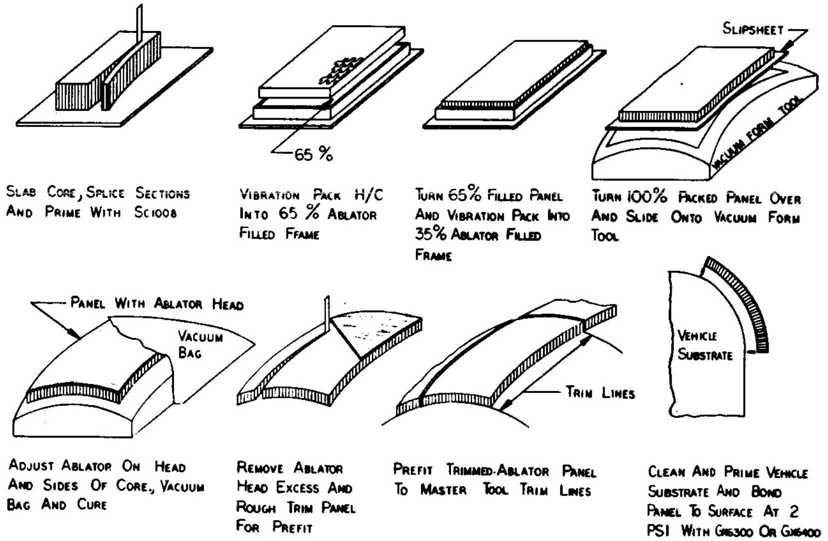

Fig. 7 Ablator Panel Fabrication Technology

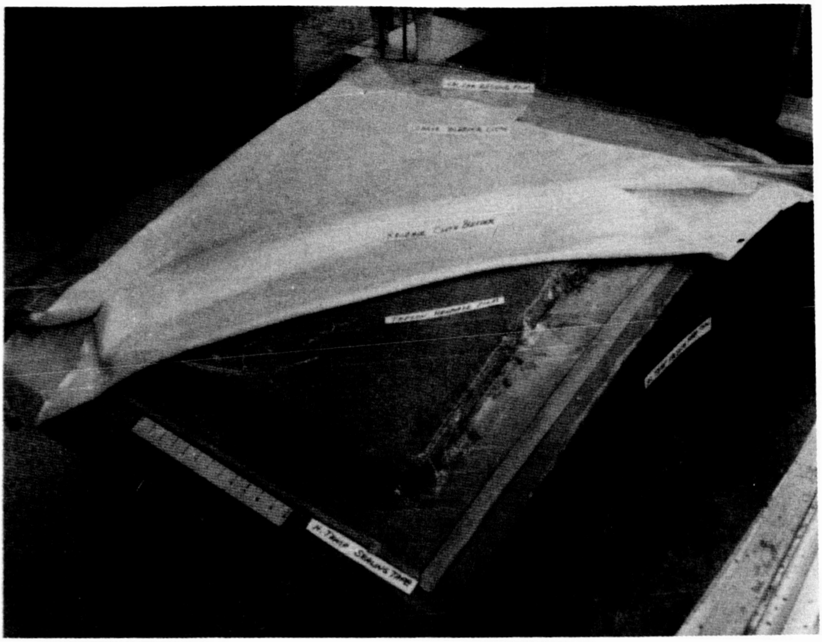

Fig. 8 Vacuum Bag Installation

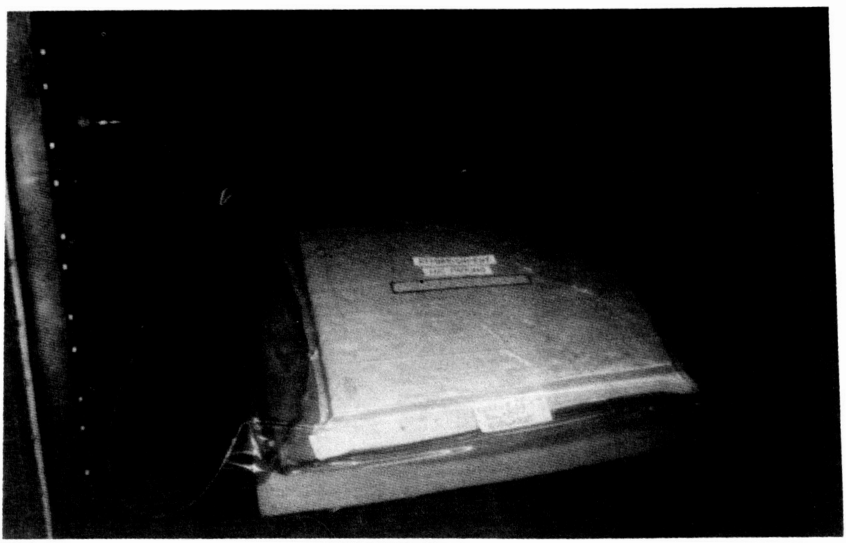

Fig. 9 Panel Being Cured in Autoclave

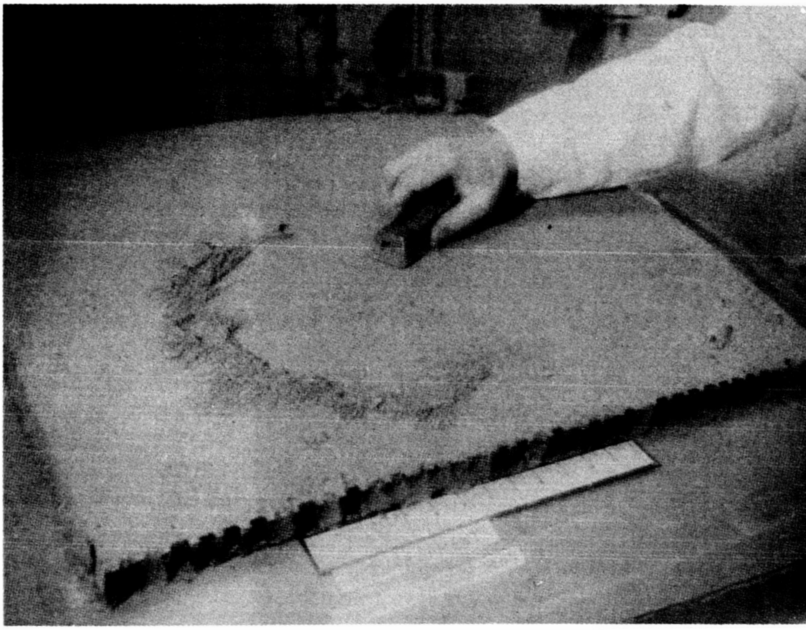

Fig. 10 Head Being Removed

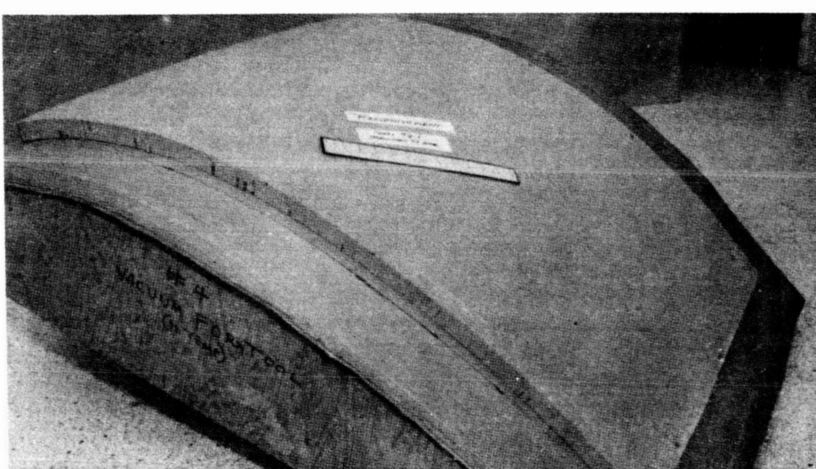

Fig. 11 Finished Panel

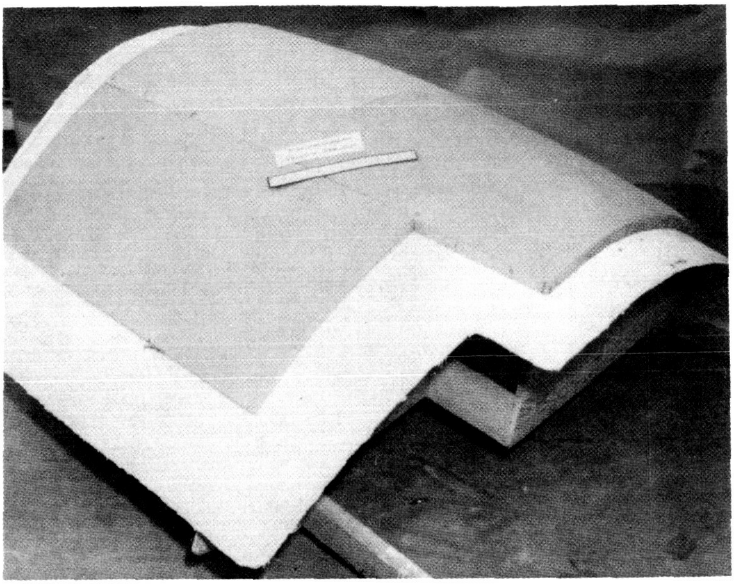

Fig. 12 Panels on Prefit Tool

The procedures just described were, of necessity, laboratory in nature and more time-consuming than would be anticipated on a production basis. In a production program the vehicle and TPS tooling would probably be made to matched master contours to ensure a proper fit and the ablator fabrication operations would be oriented toward automated procedures. The extent of this master tooling and automation would depend primarily on the number of vehicles that would require refurbishment. The higher the number of refurbishment cycles required, the more extensive the tooling could be to reduce the unit cost.

Installing the panels presented a challenge due to the size of the vehicle and the requirement that the refurbishment must be accomplished at the launch site within the short turnaround time specified for the Shuttle. Even if it were practical to place the entire vehicle in an oven to cure the adhesive used in attaching the ablative panels, this method would be precluded by the existence of on-board systems that could not survive this type of environment. As a result we decided to install the panels using a room-temperature-curing silicone RTV adhesive that requires very low pressures (1 to 2 psi) to obtain satisfactory adhesion.

The next problem was that of applying pressure on the panels until the adhesive had cured. The use of pressure plates mounted on the launch stand, or mounted to some other fixture that surrounds the vehicle, is impractical for several reasons. Since so many panels (approximately 1200), pressure plates, and load cells of one kind or another are required to completely cover the vehicle, service personnel required to work on other subsystems would be denied access to the vehicle while the thermal protection system was being refurbished. Second, this approach would also require that the vehicle be refurbished in one particular area where the pressure plate fixtures were located. Finally, a very complicated system of pressure plates and load cells would be required to completely cover the vehicle. To circumvent this type of cumbersome system, two approaches were used during this demonstration.

The first approach was to bolt pressure plates to the vehicle to restrain a pressure bag that was located between the ablator panel and the plate. When the bag was pressurized, the loads were reacted by the vehicle surface through the attaching bolts, thereby applying pressure on the ablative panel. This pressure (2.0 psi) was held for 1.0 hr while the adhesive cured, after which the plates and bag were removed from the vehicle (see Fig. 13). The access holes through the ablator were then filled with a trowelable mixture of SLA-561 ablator and allowed to cure at room temperature.

Note that this method involves pressure plates and bags for each panel with a different size, shape, and contour, and requires a study of the vehicle to determine how many common pressure plates and bags are needed.

The second method of installing the panels was the vacuum bag technique. Adhesive was trowelled on both surfaces and rolled to obtain a smooth, even coat. After applying the adhesive, the panel was positioned on the vehicle. Holding devices were not required since the panels were temporarily held in place by the adhesive, even when positioned on the bottom surface of the vehicle. A vacuum bleeder cloth and Vac-Pac bagging film, which had been fitted with a suction tube, were then placed over the panel and sealed around the edges with caulking (Fig. 14), and the assembly was evacuated using a portable vacuum pump. Vacuum pressure was maintained at 2 psi for 1 hr. (Double-backed, pressure-sensitive tape was used when bagging over adjacent ablator-covered areas to ensure adhesion of the bag and minimize leakage). After the adhesive cured, the vacuum bag was removed from the vehicle. When all the panels had been installed, the gaps between them were filled with a trowelable mixture of RTV silicone resin and filler, and allowed to cure.

The gaps were filled using a pneumatic gun (Fig. 15) equipped with a special thin nozzle that extruded the mixture into the gaps. To check the adequacy of the bond, 3/4-in.-diameter plugs were cut into the ablator at four places on each of the three panels, tension plates were bonded to the plugs, and a force gauge was attached. A load was applied by pulling on the gauge until failure occurred (Fig. 16). In each case the ablator failed just above the bond line, which is indicative of a satisfactory bond.

The next step in the refurbishment procedure was to remove the ablator from the vehicle and prepare it for reinstallation. To make the demonstration more realistic, a 2-ft by 4-ft portion of the ablator-covered area was charred using an acetylene torch.

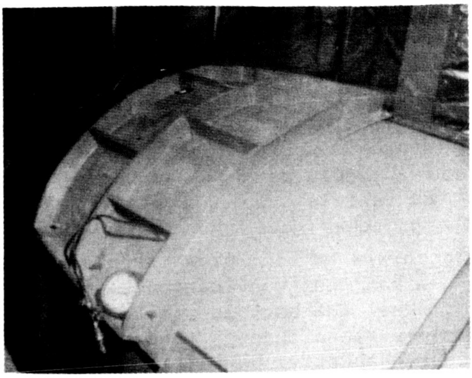

Fig. 13 Pressure Being Applied

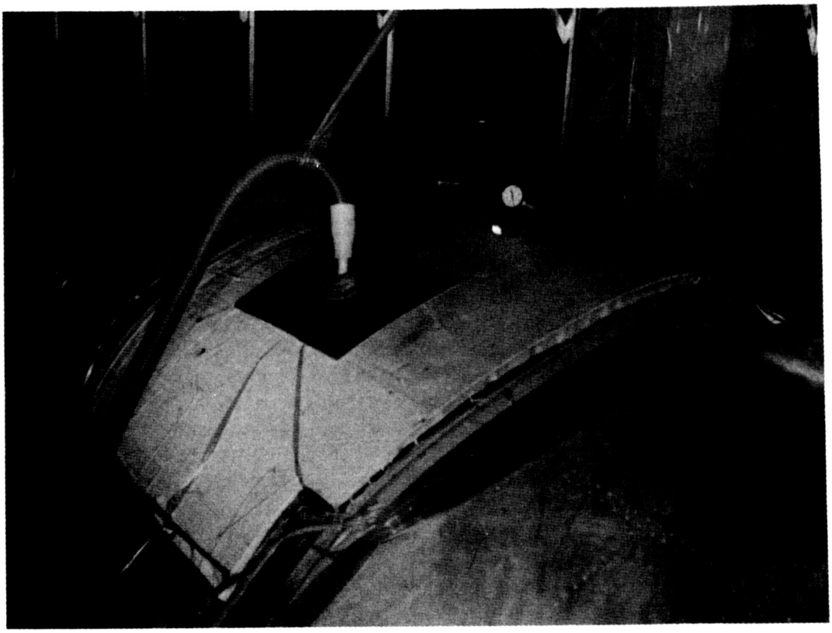

Fig. 14 Vacuum Pressure Being Applied

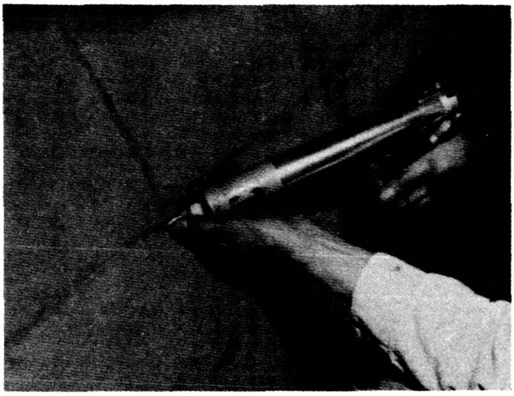

Fig. 15 Gap Filling

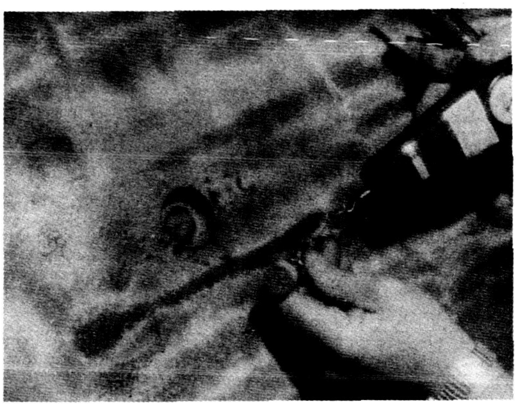

Fig. 16 Test Plug Being Removed

The standard procedure projected for the Space Shuttle involves using a rotary plane (Fig. 17) to remove the ablator in approximately 1/2-in. steps to within approximately 1/4-in. of the vehicle surface (Fig. 18); the final 1/4-in. must be removed by hand using plastic scrapers to avoid damage to the vehicle. This method is time-consuming and creates a considerable amount of dust and debris that may contaminate the vehicle. Consequently, one goal of this study was to develop a method of removing the ablator in chunks, rather than minute particles or shavings, and do it in considerably less time than with the rotary plane method.

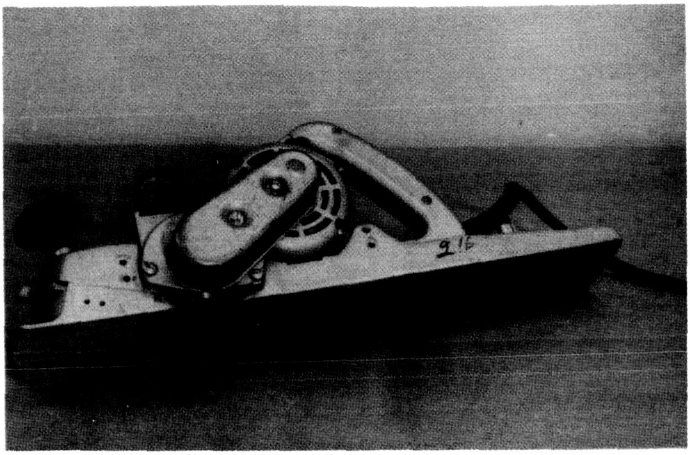

Fig. 17 Rotary Plane

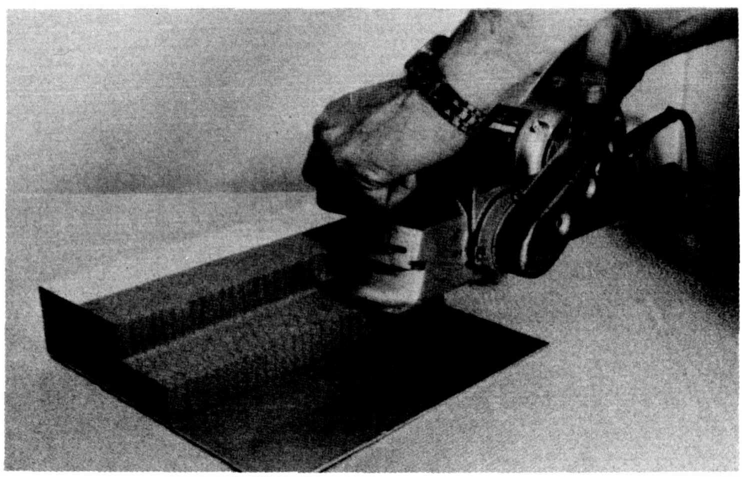

Fig. 18 Ablator Being Removed Using Rotary Plane

Several methods were tried before a successful method was actually developed. This method uses a device that slices the ablator along a line normal to the skin while a trailing wedge shears the ablator at the bond line (Fig. 19). The cutting force is applied by placing the wedge in a pneumatically driven rivet gun that is positioned and guided by the operator. Experiments indicated that strips 1¼ to 2 in. wide could be stripped off with considerable ease (Fig. 20).

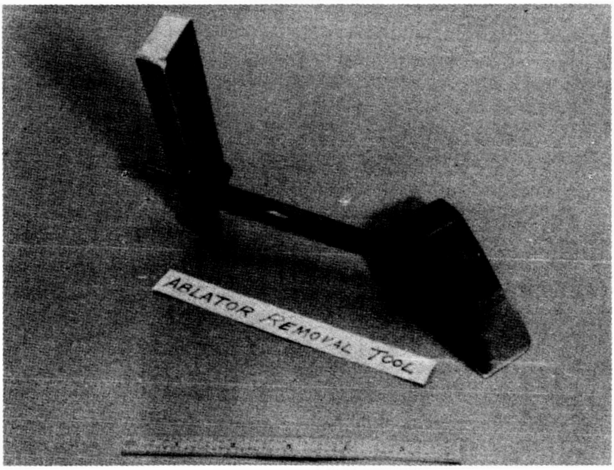

Fig. 19 Ablator Removal Tool

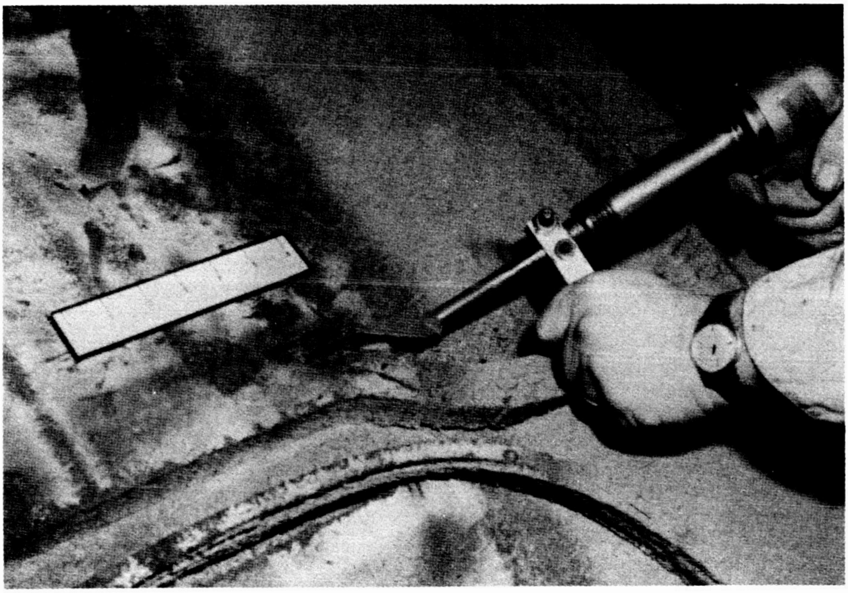

Fig. 20 Strip Being Removed

The slicing portion of the chisel is designed with a cutting edge that slopes away from the skin to reduce the risk of damaging the skin. The lower surface of the wedge portion of the chisel is flat and covered with hard plastic (cloth-reinforced epoxy) to further minimize the risk of damage. Demonstrations have shown that although the flat surface of the wedge bounces along the skin line, no damage occurs: since the breaking action of the ablator occurs above the bond line, the skin is somewhat protected by the adhesive during the removal cycle.

At this point in the demonstration study we realized that a local area of ablator must be removed before the wedge can be used since its success depends on sideways displacement of the material being removed. To do this, we designed a "U"-shaped scooping chisel (Fig. 21) to operate with the pneumatic rivet gun. To remove the ablator, a channel is first cut along the entire length of the section to be removed (Fig. 22). Another cut, 90° to the first one, is then made along the entire length of the section to be removed. This results in an "L"-shaped channel (Fig. 23) that allows ablator to be removed with the wedge chisel.

Although the scope of this program was limited to prototype development, our efforts indicated that further improvements could be obtained in several areas. First, the chisel/wedge and rivet gun could be combined into one compact unit. Various materials, such as tungsten carbide tips, could also be investigated. Next, vacuum attachments could be included to collect the small amount of minute particles generated during the removal cycle. Lazy-arm supports could also be used to reduce operator fatigue. Finally, the procedure could be automated by using tracking devices, such as those employed in the "skate" machining technique.

At this point, the demonstration on the SV-5J vehicle was carried out using the methods previously described (Fig. 24). Two complete cycles were performed; i.e., initial installation, one removal and replacement cycle, and final removal. The adhesive was removed by using plastic scrapers to remove the bulk of the residual ablator and adhesive, and the remainder was solvent-cleaned with heptane.

To demonstrate the ability to install a panel in an overhead position, one flat panel, 20 in. by 44 in., was installed on the lower left-hand flap using the vacuum-bag method (Fig. 25). No new problems were created due to the overhead position and we concluded that the one application was sufficient to demonstrate that this could be done.

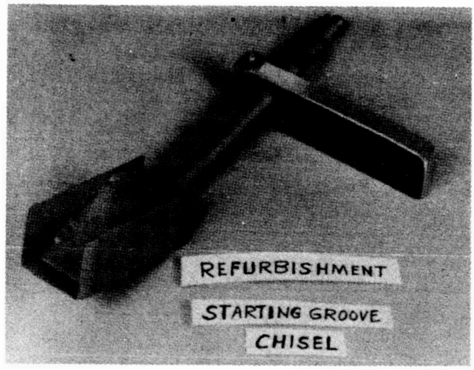

Fig. 21 "U"-Channel Starter Tool

Fig. 22 Starter Strip Being Removed

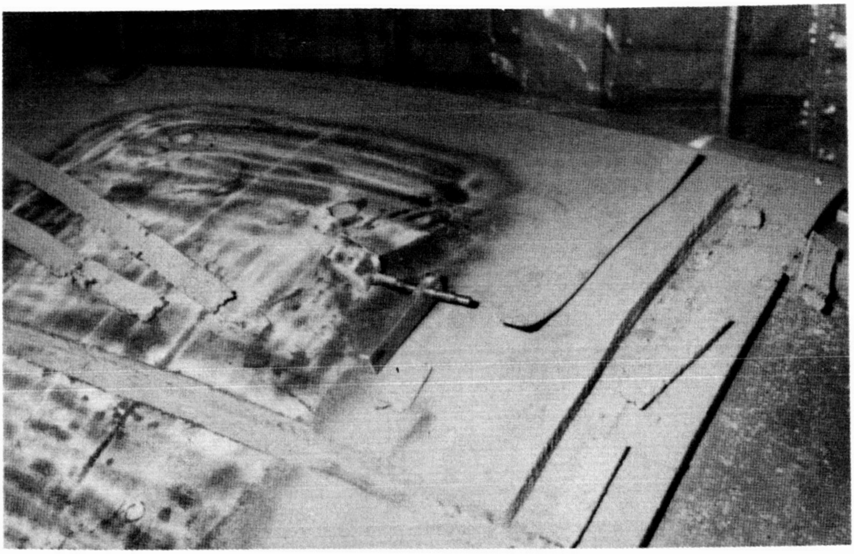

Fig. 23 Starter Strip Removed

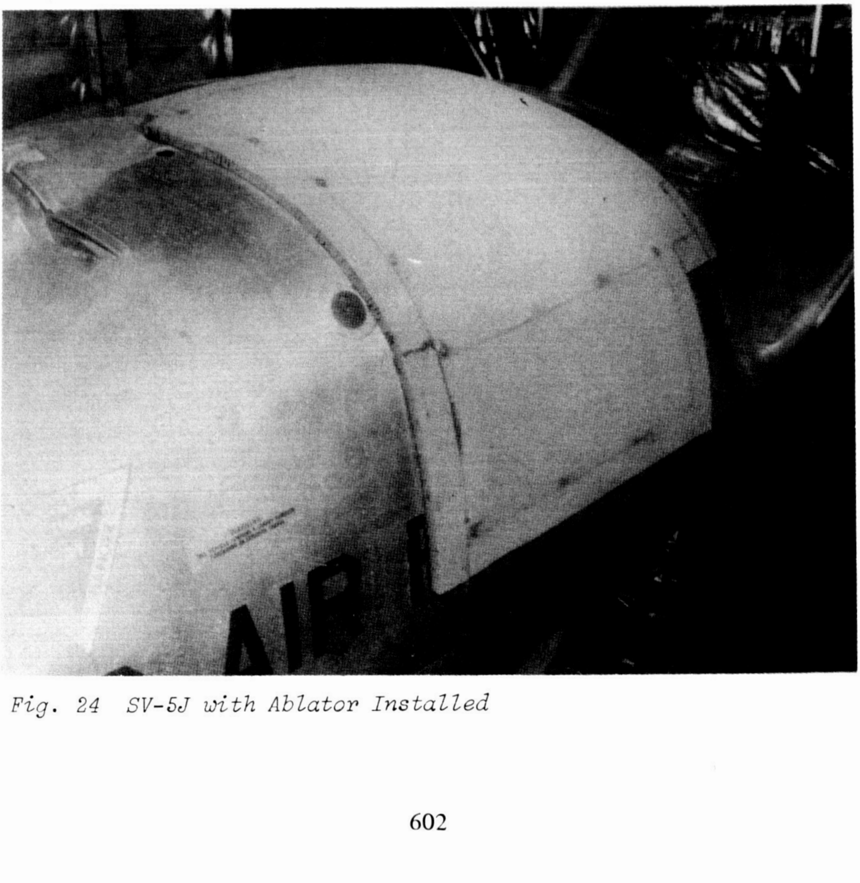

Fig. 24 SV-5J with Ablator Installed

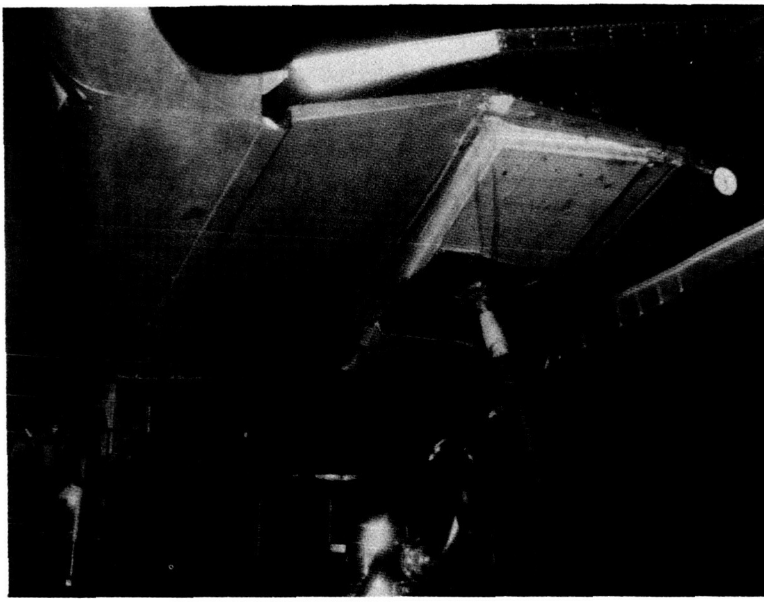

Fig. 25 Installing Panel Upside Down

COST STUDY

During the study, costs were obtained for each element of the total operation. Comparisons were made between the different methods, and the least costly methods were extrapolated for the Shuttle vehicle to obtain program operational costs, excluding DDT&E. The results of the cost analysis showed that the vacuum-bag method was by far the cheapest of the installation methods considered. Costs for this method are summarized in Table 1.

Table 1 Operational Costs for Directly Bonded Ablator (SLA 561)

ACTIVITY	PER FLIGHT	1973 DOLLARS* PER SQUARE FOOT	439 FLIGHTS
PANEL FABRICATION	$714K	$71.40	$313.4M
INSTALLATION	$ 83K	$ 8.30	$ 36.3M
REMOVAL	$ 47K	$ 4.70	$ 20.6M
TPS OPERATIONAL COST	$844K	$84.40	$370.3M

*Costs apply to acreage areas only (10,000 sq ft per vehicle), and do not include profit or fee. Comparative figures are based on vacuum-bag installation. All costs are based on 439 flights and assume an 87% learning curve.

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CONCLUSIONS

A new and unique method of fabricating, installing, and removing ablators for a space vehicle has been demonstrated in this program, and is within the realm of practical application. Some of the specific conclusions drawn from this study are as follows:

- Flat panels can successfully be shaped to fit the contours of a representative flight vehicle.

- Ablative panels can successfully be installed using pressure panels or a vacuum bag.

- The methods described in this paper can be used to remove and replace ablative panels at lower cost than previous methods.

- Besides being less expensive, these techniques also produce considerably less dust and debris.

- Ablative panels can be removed and replaced without disturbing adjacent panels.

- Further studies are required to develop nondestructive evaluation methods. The best solution at this time appears to be process control.

- Tooling should be further developed to improve efficiency and dust collection.

Specific application of an ablator on any space vehicle is contingent on its useful service life, since the ablator must be refurbished after each flight. Ablative systems are generally economical only for space vehicles where exposures to the thermal cycle are limited. Comparisons must still be made with reusable systems to determine where the ablative system ceases to be economical.

ACKNOWLEDGMENTS

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